INHABITED BUILDING DISTANCE CRITERIA AND MODERN CONSTRUCTION

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ABSTRACT

The current Inhabited Building Distance (IBD) criteria as defined by DoD 6055.9-STD is based predominately on observations, experimental work, and opinion during the period 1945 through 1969. During the last 20 years, great advances have been made in our knowledge and understanding of blast effects phenomena. During the same period, design and construction technology have changed significantly. Modern residential and commercial structures are much lighter and more flexible than the structures on which present IBD criteria are based.

In this paper, the development of IBD criteria is reviewed, and its applicability to modern construction is evaluated. Particular attention is paid to an evaluation of probable damage and risk to modern residential structures and lightweight commercial structures, such as pre-engineered buildings, sited at IBD distances.

1.0 BACKGROUND

The Department of Defense Explosives Safety Board (DDESB) publishes and maintains criteria and defines separation distances between explosive sources and various target or receiver facilities. The selection of a separation distance between donor and various classes of receivers has been evolutionary in nature and has been based predominantly on observations, experimental work and opinion during the period from 1945 through 1969. The criteria for separation distances are based on DDESB level military service opinion and judgment of acceptable damage and injury at various distances from donors.

The available technical data, social, political and legal environment that existed when the current criteria were selected are significantly different than those existing in the world today. Of particular concern is the potential for property damage and injury to the public in general at inhabited building distances (IBD). These distances apply at the boundary of military installations or storage areas where uncontrolled residential and commercial development must be accepted.

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According to the Department of Defense Ammunition and Explosives Safety Standards, DoD 6055.9-STD, at IBD, ". . . Unstrengthened buildings can be expected to sustain structural damage up to about 5 percent of replacement cost. Personnel are provided a high degree of protection from death or serious injury, with injuries that do occur principally being caused by glass breakage and building debris. . . ." [1] This damage criteria was established based on a limited section of the data base of structure types commonly constructed in the 1940-1960 period, wood frame residential construction.

The last 20 years has seen great advances in our knowledge of blast effects phenomena. Well documented experimental work and modern computer aided analysis procedures have resolved many of the technical uncertainties that existed when the present IBD criteria were established. We have also seen significant changes in design and construction technology. Modern residential and commercial structures are much lighter, are more flexible, and make greater application of glass as an exterior cladding material. The suitability of the stated damage criteria at IBD is not clear for such modern construction.

This paper is based on the results of a report prepared under the direction of the DDESB. In that report, the possible consequences of presently specified inhabited building distance criteria were evaluated, particularly as they related to modern construction. The evaluation was accomplished in four steps:

a. The historical development of IBD criteria was reviewed and discussed.

b. The empirical and analytical data used to develop the current IBD damage criteria was reviewed, and its applicability to modern construction was evaluated.

c. A cost model was prepared which compared the damage and repair costs for residences constructed during the 1945-1969 era with expected damage and repair costs for modern residential construction located at IBD.

d. Probable damage to structures other than residential construction located at IBD was evaluated. This phase of the report concentrated on modern commercial and public structures particularly susceptible to damage from blast overpressures. Examples were provided on the performance of modern pre-engineered metal buildings, a structure type proliferating rapidly in public buildings.

2.0 ORIGIN OF DoD INHABITED BUILDING DISTANCE CRITERIA

The American Table of Distances (ATD), published in 1910, provided the first industry guidelines for the siting of stores of explosives in the United States. The ATD established separation distances between explosives and inhabited buildings and public railroads. In 1914, the scope of the document was expanded to include separation distances for public highways.

The separation distances provided in the ATD were developed through a limited quantitative analysis of observed damage information obtained from previous explosive accidents. A detailed tabulation and description of these accidents are provided in Assheton's "History of Explosions on which the American Table of Distances Was Based", published in 1930.

The ATD is the source of most U.S building code siting criteria for explosive storage. It is important to note that the minimum separation distances provided in the ATD were not based upon providing absolute safety. Instead, an "acceptable" level of damage and risk was assumed. The level of protection which would be provided at separation distances was described ". . . as preventing serious risk to life and limb and as preventing substantial building damage." [2] Separation distances were developed based upon the assumption that ". . . personnel within a building will not be seriously injured if that building does not experience substantial damage." [3]

A significant feature of the separation distances provided in the ATD was the credit given for the barricading of explosives. At that time, it was believed that intervening barricades would not only reduce debris, but would also attenuate blast overpressure at any given distance by at least 50 percent. As a result, the document, while providing separation distances for barricaded explosives only, recommended that these distances be doubled for unbarricaded explosives.

Public safety concerns following the Lake Denmark accident on 10 July 1926 prompted Congress to establish the forerunner of today's DDESB. On 3 March 1928, this body recommended to Congress that the explosive safety laws of New Jersey, which were based on ATD criteria, be adapted for use by the Armed Forces. The inhabited building distances provided in the resulting regulations remained essentially unchanged through the end of World War II.

During the 1940's, an extensive reappraisal of ATD criteria was conducted by the Army-Navy Explosives Safety Board (ANESB). In a paper prepared by Colonel Clark S. Robinson and published on 1 July 1945, a critical analysis was made of the American Table of Distances siting criteria. In this report, additional data were presented and analyzed for 66 explosions which had occurred since the initial publication of the American Table of Distances. Although no recommendations were given for new criteria, Colonel Robinson concluded that ". . . the American Table of Distances on the unbarricaded basis gives unnecessarily great distances for small quantities of explosives, but for large quantities it is grossly inadequate. . . The safety distances prescribed by the British War Office recognize this situation and, (where great concentrations are involved) require from 3 to 4 times the distance required in this country." [4]

In addition, Colonel Robinson raised the first significant doubt of the credit given to barricades in the ATD. In his report, he stated that ". . . it is now generally recognized that, except in very special circumstances, barricades around the explosive are of no effect in reducing the maximum distance at which structural damage occurs." [5]

As a result of questions raised by Colonel Robinson, an intensive effort was undertaken by the ANESB to review ATD criteria and, if needed, to develop new, more accurate criteria. On 1 July 1948, Dr. Ralph Ilsley, a member of the Board, issued a report entitled, "Reappraisal of the American Table of Distances and Recommended Bases for Discussion, Modification, and Final Approval of Minimum Risk Distances for Handling and Storing Military Explosives and Ammunition".

In his report Dr. Ilsley recommended "that the minimum distance for which the magnitude of the hazard from explosions - structural damage, flying glass, and missiles - can be accepted is represented by a risk factor of 50. (Distance from explosion in feet = 50 $W^{1/3}$. W = weight of explosives in lbs.)" Dr. Ilsley recommended that this "risk factor" be applied to residences and houses which are inhabited by families, to public highways, and to public railroads. He also recommended that the following increased "risk factors" be applied: "For above ground magazines of hollow tile construction, the risk factor shall be 85. For large storage reservoirs with wooden roofs, the risk factor shall be 200. For hangars the risk factor shall be 200. Buildings where people are accustomed to gather and which have a relatively large glass exposure - schools, hospitals, factories, railroad stations, churches, etc., - shall not be located between distances represented by risk factors of 50 and 100 unless suitable interior screens are placed in back of the windows to reduce the flying glass hazard." [6] Dr. Ilsley's report, along with results of additional full-scale tests conducted during the 1940's, prompted the renamed Armed Service Explosives Safety Board (ASESB) to recommend a revision to the DoD application of ATD criteria in April 1950.

The 1950 revision incorporated Dr. Ilsley's recommendation that increased quantity-distance criteria be used for certain high risk structures to ensure that they and their occupants receive comparable levels of protection. The revision provided the following discussion of siting requirements for high risk structures.

> The inhabited building distances recommended in Table No. 1 [which were based on an IBD distance of $50W^{1/3}$] give little protection from the hazard of flying glass in schools, hospitals, and factories unless windows have safety glass or adequate interior screens; and unless of a substantial construction give insufficient protection from structural damage to large buildings such as churches, theaters, railroad stations, assembly halls; and insufficient protection to hollow tile magazines, storehouses, and large oil or water storage reservoirs with exposed wooden roofs, or to airplane hangars. If because of their occupancy or vulnerability a reasonable degree of protection, comparable to that of dwellings and other

buildings, is desired for the structures indicated below, the distances must be changed as follows:

(1) School, hospitals, and factories - $d = 100\ W^{1/3}$ (unless provided with safety glass or interior screens)

(2) Large churches, theatres, railroad stations, and assembly halls - $d = 100\ W^{1/3}$

(3) Hollow tile magazines and storehouses - $d = 85\ W^{1/3}$

(4) Large oil or water storage tanks with exposed wooden roofs - $d = 200\ W^{1/3}$

(5) Large airplane hangars - $d = 200\ W^{1/3}$ [7]

The 1950 revision was accepted by the Air Force and the Navy with the added stipulation that a constant, minimum distance of 1235' be required for unbarricaded explosives to provide protection from fragments. The Army, however, disagreed with the validity of the recommendations and resisted any change from ATD criteria.

The disagreement between the military services on IBD criteria continued until 1955. On 11 October 1955, Colonel Ronald B. Currens, Chairman of the ASESB, exercised his right to decide issues on which the services could not reach unanimous agreement and issued a memorandum in which he required that the ATD be used to provide IBD protection for unbarricaded explosive concentrations. In addition, the memorandum required that no constant distance be specified to provide IBD protection for missiles.

On 7 December 1956, the first quantity-distance standard for the Department of Defense (DoD 4145.17) was published. This standard differed substantially from the 1950 criteria as implemented by the Navy and Air Force. Among changes, the minimum fragment distance of 1235' for unbarricaded explosives was dropped. Instead, inhabited building distances reverted to previous ATD criteria. Unbarricaded inhabited building distances were once again given as twice those required for barricaded explosives. In addition, a minimum explosive weight of 50 pounds was introduced. This minimum weight resulted in a minimum inhabited building distance of about 150' for barricaded explosives and 300' for unbarricaded explosives.

The 1956 criteria also deleted any distinction between different types of inhabited buildings. As a result, residences, churches, schools, factories, and other structures were all allowed to be sited at the same IBD requirements. The assessment of risk for different types of structures, as developed by Dr. Ilsley, was abandoned.

On 11 March 1966, a revision to the 1956 DoD explosive safety criteria, DoD 4145.23, was issued. This revision continued to use ATD criteria to credit barricades with reducing both blast and fragment hazards at inhabited building distances.

During the 1960's, there was increasing concern among members of the ASESB that barricades were not as effective in reducing blast overpressures as was assumed in the ATD. In response to this concern, the Board funded an extensive study to address the effectiveness of barricades issue.

On 12 July 1966, the ASESB was presented with a detailed analysis of the effectiveness of barricades in reducing blast overpressures at inhabited building distances. [8] The analysis concluded (as had earlier work) that at inhabited building distances, a typical barricade would not provide any reduction in blast overpressures. Missile hazards were not addressed in the analysis. Since the 1966 revision of DoD explosive safety criteria credited barricades with reducing blast overpressures at inhabited building distances, it was apparent that at least a portion of the IBD requirements was in error.

Despite the evidence that barricades would not reduce blast overpressures at IBD's, the 1969 revision, DoD 4145.27M. continued to give them the same credit as had been allowed in previous standards. During this time, there was serious disagreement among members of the ASESB as to what new standards should take the place of the ATD criteria. Members were unsure if IBD's should be based on ATD barricaded distances, ATD unbarricaded distances, or some new criteria.

In order to resolve this issue, the ASESB established its own working group in 1969 and gave it the mission of recommending new quantity-distance standards for unbarricaded explosives. It reported its findings to the ASESB on 28 February 1969.

In their recommendations, the group proposed extensive changes to the inhabited building distances given in the 1969 explosives safety document. They returned to Dr. Ilsley's 1948 recommendation that special IBD criteria be developed for structures particularly vulnerable to blast overpressures. In their report, the group stated that ". . . Consideration should be given to a specific analysis of buildings with large expanses of window glass, large unsupported roof structures, and certain wall construction that is particularly vulnerable to blast overpressure; and the distance requirements should be increased in these instances so that a comparable degree of protection limiting structural damage and risk to personnel to levels expected for more standard construction at inhabited building distance is achieved. . .". [9] "Standard" construction here is either the widely applied "residential construction" or the ill-defined "substantial construction".

On 10 June 1969, the following IBD criteria were recommended for adoption by the Board "in the event barricades are proved ineffective":

a. A fixed minimum distance of 865' for up to 10,000 pounds of unbarricaded explosives to mitigate fragmentation hazards,

b. IBD of 40 $W^{1/3}$ from 0 to 10,000 pounds for barricaded explosives,

c. IBD of 40 $W^{1/3}$ from 10,000 to 100,000 pounds (barricaded or unbarricaded explosives),

d. IBD increasing from 40 $W^{1/3}$ to 50 $W^{1/3}$ for 100,000 to 250,000 pounds (barricaded or unbarricaded explosives),

e. IBD of 50 $W^{1/3}$ for 250,000 to 500,000 pounds (barricaded or unbarricaded explosives). [10]

As can be seen, the 1969 ASESB proposal deleted the working group's recommendation that comparable levels of protection be provided to higher risk structures. In discussions leading up to this decision, several Board members expressed concern that the acceptance of siting for consistent risk would have a very detrimental impact on the siting of explosives at military installations. To avoid such problems, it was decided that inhabited building distances would be the same regardless of the vulnerability of the receptor structure to blast overpressures. In addition, the IBD selected was the lower limit of all the possible choices.

Following further review, all of the Board's IBD recommendations except the fixed minimum fragment distance of 865' were included in Interim Change 1-5 to the 1969 criteria. As a result of this change, there was a significant relaxation of IBD safety criteria for blast overpressures. Unbarricaded IBD distances based upon overpressure for weights less than 100,000 pounds were reduced from 70 $W^{1/3}$ to 40 $W^{1/3}$ or by more than 40 percent. For weights exceeding 250,000 pounds, the new IBD criteria required a minimum separation distance of 50 $W^{1/3}$ while the old criteria for unbarricaded explosives had required a minimum separation distance of 70 $W^{1/3}$.

The 1974 revision to DoD explosive safety criteria incorporated Interim change 1-5. In addition, this revision substantially strengthened fragmentation safety requirements. Interim Change 1 to the 1974 document, issued on 26 November 1975, established 1250' as a "default" minimum distance for protection from both primary fragments and building debris.

Since the 1974 revision, no changes have been made to IBD distances for protection from overpressures. The "default" IBD fragmentation distance has, however, been reduced for explosive quantities of 100 pounds or less. For these quantities, the minimum IBD distance for protection from fragments is now 670'. For explosive quantities in excess of 100 pounds, the "default" minimum distance of 1250' remains in effect. As a result, minimum IBD distances for protection from fragments will control for explosive weights of up to 30,000 pounds while IBD distances for protection from overpressures will control thereafter.

The general evolution of IBD criteria is shown in Table 2.1. In this table, inhabited building distances from the American Table of Distances (ATD), from Dr. Ilsley's 1948 recommendation, and from the current safety document, DoD 6055.9-STD are compared and contrasted.

TYPE OF CONSTRUCTION	ATD	ILSLEY RECOM.	DoD 6055.9
Residential Construction:			
- Barricaded	35	50	40-50
- Unbarricaded	70	50	40-50
Buildings with Many People and Large Glass Exposure:			
- Barricaded	35	50-100*	40-50
- Unbarricaded	70	50-100*	40-50
Large Storage Reservoirs with Wooden Roofs and Hangars:			
	N/A	200	40-50

* Use scaled distance of 100 $W^{1/3}$ unless suitable interior screens are placed behind windows to reduce flying glass hazard.

Table 2.1 - Comparison of IBD scaled distances based on overpressure.

3.0 DAMAGE TO RESIDENTIAL STRUCTURES AT INHABITED BUILDING DISTANCES

In this portion of the report, expected damage and repair costs will be developed for older and modern residential construction damaged at inhabited building distances. The analysis will include a comparison of the expected damage and repair costs to those assumed by present IBD criteria.

3.1 "House Damage Assessment" by C. Wilton and B.L. Gabrielson, 1972 [11]

In this extensive and well documented report, the results of numerous studies on damage to residential structures from air blast loadings were compiled. These studies had been conducted over the previous 21 years. They included data on the response of residential structures to both conventional and nuclear detonations. Tests included in this compilation were sponsored by several government agencies including the Defense Nuclear Agency, the Atomic Energy Commission, the DDESB, and the Civil Defense Preparedness Agency.

Four of the houses discussed in the report were located either at or within a few percent of their present inhabited building distance based on overpressure. As expected, the windows facing the blast loading were destroyed in each of these houses with some of the side and rear windows also damaged. In addition, each house reported some damage to window casings with two houses also reporting damage to front and interior doors.

Plaster cracking was reported in all of the houses with extensive plaster damage reported in some rooms. Roof rafters were damaged in three of the houses with one house reporting one broken rafter and the other two houses each reporting seven broken rafters.

It should be noted that the test houses were constructed of a higher grade of lumber than is normally used on modern residential construction. These houses employed No. 2 lumber while wood graded as No. 3 or lower is normally used in modern construction. Interestingly, the broken rafters tended to fail along knots on the tension side, near the central portion of the member. Lumber used on modern residential construction would normally have more knots and other defects than No. 2 lumber, and therefore, one would expect more of these rafters to fail under blast loading.

It is also important to remember that standard dressed sizes for dimensions less than 6" have decreased since the referenced testing was conducted. In the early 1970's, standard dressed sizes for dry lumber were reduced from the nominal dimension less 3/8" to the nominal dimension less 1/2" for dimensions less than 6". Therefore, a nominal 2 x 4 previously required to have a minimum standard dressed size of 1-5/8" x 3-5/8" is now only required to be 1-1/2" x 3-1/2". In terms of section properties, this change results in a reduction in moment capacity for a 2 x 4 of approximately 17 percent. For this reason, modern 2 x 4's will have a lower capacity than the older 2 x 4's used in the test houses.

3.2 "Blast Damage Assessment Procedures for Common Construction Categories" by Southwest Research Institute, 1987 [12]

The information provided in this report was developed to assist the Navy in assessing the vulnerability of its facilities to terrorist attack. The report was based on a maximum external surface explosion of 4,000 pounds of TNT. Included in this effort was the development of pressure-impulse (P-I) diagrams for various structure types.

P-I diagrams represent the dynamic response of different types of structural elements when exposed to a given overpressure and impulse. These diagrams must be developed for each structural element or system. They consist of one asymptote defining the response of the element to pressure load and another for impulse load. These two limiting responses are connected by a transition region where both impulse and pressure influence response. Using these diagrams, one can quickly estimate the expected level of damage to a structure subjected to a given overpressure and impulse.

One limitation of this method is that under very long duration pressure loads, the resistance of a structure will tend to degrade. This effect has been well documented in many nuclear tests and simulations and has led to the use of vulnerability parameters that account for such degradation. The effect would be more pronounced as the donor becomes very large, i.e. a million pounds or more. We will ignore this effect in this section of our report.

Among P-I diagrams developed for this report is one for wood walls. The percentage damage curves on this diagram were largely developed using data from the "House Damage Assessment" report discussed in the previous section. In order to illustrate changes in residential construction, the P-I diagram has been modified in Figure 3.1 to represent the wall of a typical residential structure constructed prior to 1970. For this wall, 2 x 4 studs eight feet in length are spaced at 16", 3/4" wood diagonal sheathing is used, and the interior wall is assumed to be 3/8" plaster over 3/8" wood lath.

In comparison, Figure 3.2 provides the P-I diagram for the wall of a typical modern residential structure. For this wall, 2 x 4 studs eight feet in length are again spaced at 16", but the exterior of the house is assumed to be 1/2" insulating board sheathing covered by vinyl siding. This represents a typical exterior cladding in modern residential construction. The interior walls are assumed to be 1/2" gypsum board.

Through comparing Figures 3.1 and 3.2, it is apparent that modern residential construction will suffer significantly more damage under blast loading than older construction. In order to provide some frame of reference, a data point has been provided for each curve. This data point represents the pressure and impulse at the IBD overpressure distance for 4,000 pounds TNT.

There are two reasons for this increased damage. In older structures, the studs and diagonal sheathing act as a composite section under blast loadings, while the studs and insulating board used in modern construction will respond independently. In addition, as we have mentioned, modern wood wall studs have a reduced section.

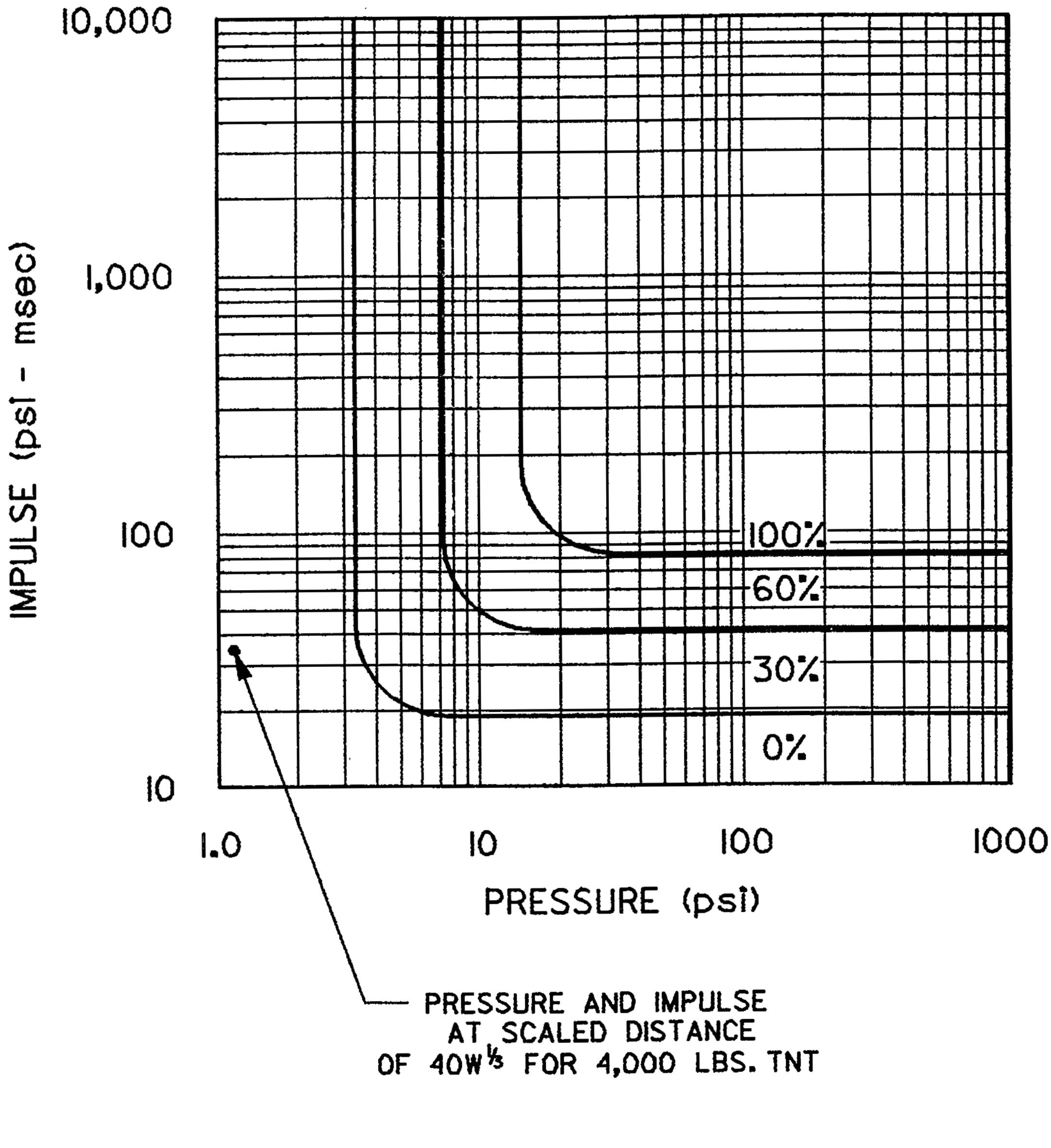

Figure 3.1 - Pressure-Impulse Diagram for older residential wall construction (Curves separate different percentages of structural damage).

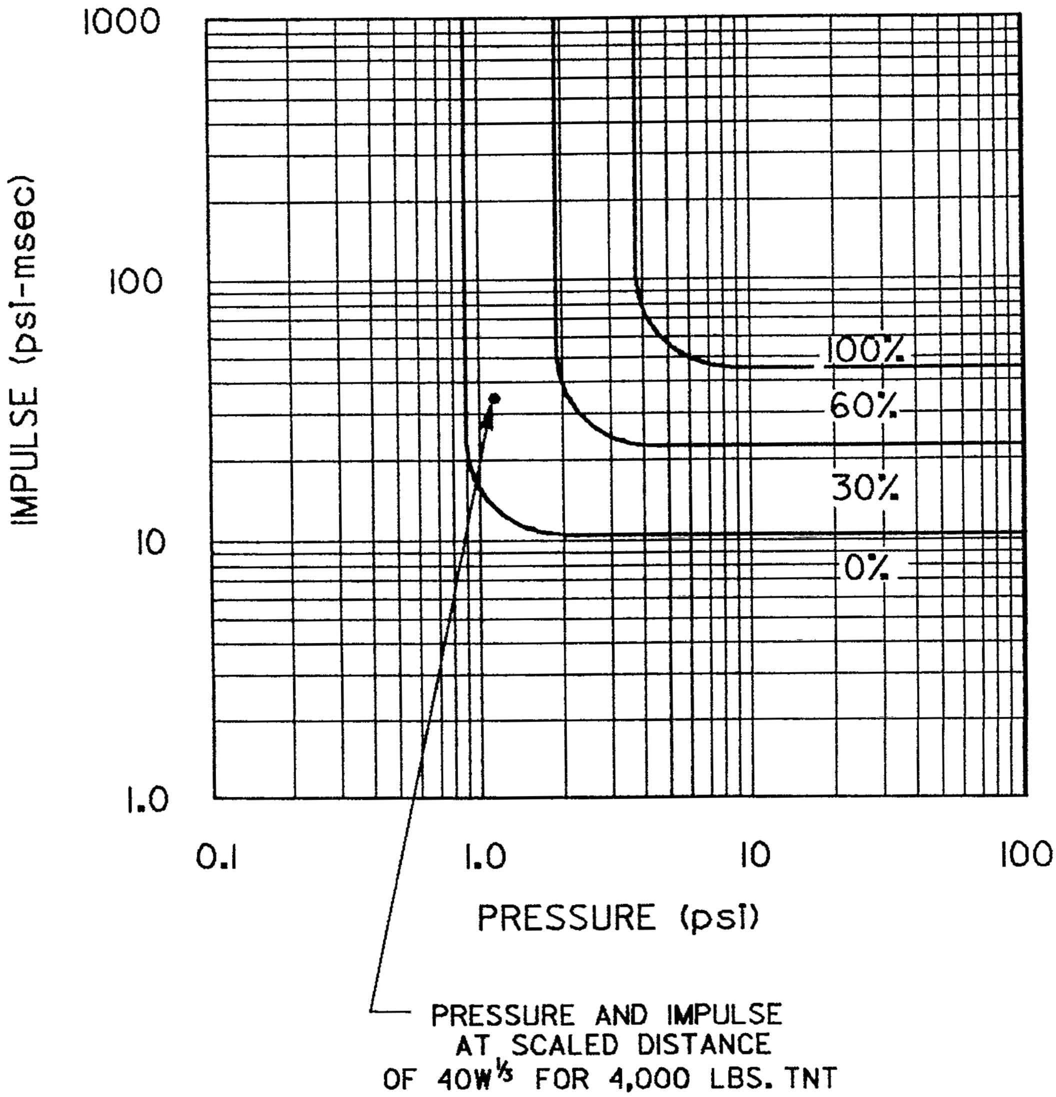

Figure 3.2 - Pressure-Impulse Diagram for modern residential wall construction (Curves separate different percentages of structural damage).

An examination of the limiting values in Figures 3.1 and 3.2 provides a striking comparison of the reduction in resistance of modern residential construction. The asymptote defining resistance to long duration pressure load is approximately 3.2 psi for the older wall construction; for the modern wall system, it is about 0.9 psi. The newer wall framing has only 28 percent of the resistance of the older system. Similarly, the impulse resistance has been reduced from 19 psi-msec to 11 psi-msec, or to about 57 percent of the previous resistance. For large quantities of stored explosives, almost all building structural elements are pressure sensitive rather than impulse sensitive. Thus, the degradation in pressure resistance is more significant. Unfortunately, present IBD distances are based on expected damage to the older, more substantial residential structures.

3.3 Comparison of Residential Repair Costs at IBD

In order to evaluate probable repair costs for older and modern residential construction, a comparison has been made of expected damages and repair costs for a 1945-69 era house and for a modern house damaged at their IBD distance. Data on the older house were obtained from the "House Damage Assessment" report discussed under section 3.1. In the analysis, the average damage and repair cost for Houses I-5 and I-6 were used. These houses were chosen because they were located at their IBD overpressure distance, the damage reported for each house was from a single event (instead of the worst of four events as was reported for Houses I-10 and I-11), and the quantity of explosives detonated was low (10,000 pounds), thereby providing a conservative analysis.

For the modern house, data developed from contacts with insurance companies along with the data developed earlier in this report were used to estimate damage to a house similar to Houses I-5 and I-6 but constructed of typical modern construction materials. The modern house was evaluated for the same blast loading as the older house. Expected damage and repair costs for the older and modern house are compared in Table 3.1.

In reviewing Table 3.1, it can be seen that increased damage to the modern house was expected for "roof framing and roof surface", "exterior and interior wall framing", and "interior plaster". As was discussed under section 3.2, the increased damage to wall framing and plaster is primarily due to the change from the plaster on wood lath and wood sheathing typical of older construction to the gypsum board and insulating board sheathing typical of modern construction. Damage to the remaining structural elements was conservatively assumed to be unchanged. Even with this conservative assumption, the estimated cost to repair structural damage increased from 5.8 percent to 10.0 percent of the house replacement cost. For larger explosive quantities, damage at IBD distances would be even greater due to the increase in the loading duration.

ITEM	OBJECTIVE VALUE (% OF TOTAL)	% DAMAGE (OLDER CONST.)	% CHANGE (OLDER CONST.)	% DAMAGE (MODERN CONST.)	% CHANGE (MODERN CONST.)
Floor and Ceiling Framing	17.0	0	0	0	0
Roof Framing and Roof Surface	7.0	2	0.1	10	0.7
Exterior and Interior Wall Framing	16.0	0	0	10	1.6
Interior Plaster	11.0	6	0.7	16	1.8
Exterior Sheathing and Siding	8.6	0	0	10	0.9
Foundation and Basement	19.0	0	0	0	0
Misc.: Stairs, Paint, Fireplace, Trim	12.0	13.5	1.6	13.5	1.6
Doors	4.6	20	0.9	20	0.9
Windows	4.8	52.5	2.5	52.5	2.5
TOTAL	**100.0**		**5.8**		**10.0**

Table 3.1 - Comparison of estimated costs to repair structural damage to older and modern residential structures damaged at IBD distances. (Note: Costs do not consider damage to furnishings.)

4.0 DAMAGE TO MODERN PRE-ENGINEERED BUILDINGS AT INHABITED BUILDING DISTANCES

During the last twenty years, the application of pre-engineered steel buildings has spread rapidly from its initial use in light industrial building. It is now commonly employed for all types of low rise buildings (less than three stories) including public and commercial office space, retail space and shopping malls, churches, schools, gymnasiums, and libraries.

Pre-engineered buildings can be constructed with glass or masonry curtain walls to provide an attractive appearance. They are designed to an industry standard developed by the Metal Building Manufacturers Association (MBMA) which uses less conservatism in load development than standard design codes. As a result, while they are adequate for code loadings, they have little reserve capacity.

Pre-engineered buildings represent a significant cross section of all new non-residential construction. This type of construction is now estimated to account for more than 50 percent of all new low rise non-residential construction in the United States.

To provide an engineering assessment of IBD performance for this type of non-residential structure, an analysis has been performed on a typical long span, pre-engineered building. The design of this building was prepared under contract and was reviewed by our office. It has recently been constructed at Aberdeen Proving Ground. The structure would be representative of a moderate size commercial building such as a gymnasium or a shopping mall.

The building has plan dimensions of 170'-6" x 302'-6" and varies in height from approximately 19'-2" to 27'-6". The main roof support beams span the 170'-6" dimension and are supported at both ends and at their approximate center. These beams are spaced at 20'-0".

The main roof support beams are I-beams with varying flange and web dimensions. The webs have a high depth to thickness ratio and are, therefore, particularly susceptible to buckling under loading if not properly braced. The roof purlins brace the top flange of the beam in addition to supporting the roof deck. This system is typical of those used in modern pre-engineered buildings.

There are three different structural elements that make up the structural system of such a building:

a. Wall panels and roof decking

b. Wall panel support beams (girts) and roof deck support beams (purlins)

c. Primary framing columns and roof beams

The wall panels and roof decking receive the blast load and transfer it to the girts and purlins which in turn transfer it to the columns and roof beams. These elements can only transfer load to supporting members equal to their capacity.

In our initial analysis, it was assumed that the roof deck and purlins which frame into the roof support beams would fully transfer the blast load on them. The validity of this assumption will be discussed later in this section. The roof beams were assumed to develop their full plastic capacity under loading. This is a very optimistic assumption and will result in an upper bound on load capacity.

Our results were as follows. If the building roof beam system were located at the minimum IBD scaled distance of 40 $W^{1/3}$ from a 30,000 pound detonation, its maximum dynamic deflection would be approximately 9'-11". The roof beams would likely collapse prior to reaching this deflection. Even if collapse did not occur, replacement would obviously be required. The roof beams would have to be located at a scaled distance in excess of 100 $W^{1/3}$ from the detonation before they would escape permanent structural damage.

If the building were located at the minimum IBD scaled distance of 50 $W^{1/3}$ from a 500,000 pound detonation, its calculated maximum dynamic deflection would exceed the building height; collapse of the roof system would occur. For these roof beams to escape permanent structural damage, the building would have to be located at a scaled distance well in excess of 100 $W^{1/3}$ from the detonation.

An analysis was also performed on a typical wall panel, wall purlin, roof deck, and roof purlin. Properties used in analyzing these structural elements were developed from the Armco Building Systems and Products Design Manual. Armco is one of the largest suppliers of metal building systems. These elements are representative of those most commonly used in modern pre-engineered building construction.

The elements were analyzed at a scaled distance of 40 $W^{1/3}$ from a 30,000 pound detonation. Results were as follows. The roof purlins underwent a maximum dynamic inelastic deflection of 14.7" over a 20' span. Obviously, these purlins and the supported deck would have to be replaced. If the roof purlins were not damaged (i.e., were much stronger and provided the needed support to the roof deck), the roof deck would fare much better and would likely suffer no permanent damage. However, this would then assure that all loads were transferred to the main roof beams with the consequences described earlier.

The wall girts would collapse under the loading; the maximum dynamic deflection calculated for these elements exceeded their span length. Assuming the wall girts were not damaged, the wall panels would undergo a maximum dynamic deflection of approximately 4.8" over a 12' span and would require replacement.

In a typical design condition, the wall panels, wall girts, and roof purlins would be substantially damaged and would require replacement. They would not transfer sufficient load to fail the frame members. Since, however, the purlins and girts provide critical bracing for the framing columns and roof beams, there is a high risk of collapse due to instability.

The major conclusions of our analysis are as follows. Modern pre-engineered metal building systems are extremely vulnerable to serious damage at current IBD criteria for quantities of explosive above 30,000 pounds. Major damage would be expected to facing and parallel walls and all roofing and supporting members. Replacement of these elements would likely be required. The repair cost could exceed 50 percent of the original cost of the structure. Damage to contents would increase this percentage even further.

Based on the foregoing analysis, it would be necessary to site a modern pre-engineered commercial building at a scaled distance in excess of 100 $W^{1/3}$ from a standard Army magazine to provide a level of risk consistent with IBD criteria. In a port siting situation where loading of munitions for transport by ship is present, the required scaled distance would be significantly larger due to the greater quantity of explosives involved and the resulting increase in loading duration.

The expanded use of this type building system for applications where large numbers of people are present is inevitable due to its low initial cost and speed of erection. Further, the level of probable damage leads to a risk of injury to occupants which is significantly higher than the current standard assumes at IBD.

5.0 CONCLUSIONS

The explosive safety quantity-distance criteria presented in DoD 6055.9-STD evolved from the original American Table of Distances first published in 1910. During the period from 1945 through 1969, substantial technical data and criteria were developed which clearly indicated that modification of the older ATD criteria was required to reflect the increase in the damage data base for large explosions and observations from full scale tests. The most significant results from this period were the recognition of the negligible value of barricades, the risk of greater damage to specialized structures, and the risk when large amounts of glass were present in a building.

In the years since the current IBD criteria were formalized, modern construction materials and construction methods have resulted in structures which are much lighter and more vulnerable to overpressure. Our literature search, analysis, and design experience have confirmed that damage to many modern residential, public, and commercial buildings will be greater than that described in the current standard.

Our calculations indicate that structural damage to modern residential construction will almost double compared to structures on which the current standard is based. In addition to this increase in replacement cost for the structure, other costs will be incurred which were not considered in the original standard. These costs include replacement of furnishing such as curtains, carpet, and furniture. Insurers will pay these expenses and then seek recovery from the government. Property owners will seek recovery for real or perceived damage not covered by their insurer.

While damage cost increases are a concern for residential construction, a more serious concern exists over commercial-public buildings. Construction materials and design techniques for these structures have advanced rapidly and have resulted in very low cost, lightweight structures. These structures are now widely used for schools, gymnasiums, shopping malls, restaurants, etc.

Many of these structures also have a very large percentage of glass in their curtain wall system. It is now common to see curtain wall systems which are 50 to 70 percent glass. Risk of injury for occupants of both lightweight steel structures and structures with glass curtain walls is much greater than that presumed in the existing standard. The potential for serious injury or structural collapse is high for large quantities of explosives at current IBD. The present standard is not adequate to address these risks. Many other conventional structures described by Dr. Ilsley in 1948 are also still subjected to these same risks.

The research and analysis provided in this report can be summarized as follows. First, a large percentage of modern residential, commercial, and public construction will suffer damage substantially in excess of the 5 percent criteria postulated in the current IBD standard. Second, associated with that increased damage will be a greater risk of personnel injury. These conclusions are particularly applicable to quantities of explosives in excess of 30,000 pounds.

6.0 ACKNOWLEDGMENTS

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